

X-ray sources in ω Centauri and other globular clusters

Frank Verbunt

*Astronomical Institute, Utrecht University, Postbox 80.000, 3508 TA
 Utrecht, The Netherlands; email verbunt@phys.uu.nl*

Abstract. X-ray bursts from bright sources in globular clusters of our galaxy show that at least 11 (of a total 13) of these sources are neutron stars. One of the low-luminosity X-ray sources in ω Cen is a neutron star accreting at a low rate. Together with the discoveries that M 15 contains two bright X-ray sources, and that 47 Tuc and NGC 6440 contain 2 and 5 low-luminosity X-ray sources with a neutron star, this indicates that the total number of binaries with neutron stars in globular clusters is higher than previously suspected. The discovery of very bright X-ray sources in globular clusters near other galaxies indicates that these clusters contain binaries with accreting black holes, and multiple bright X-ray sources. Dozens of low-luminosity X-ray sources have been discovered in ω Cen, NGC 6397, NGC 6752, NGC 6440, and a hundred in 47 Tuc. Accurate Chandra positions of these sources combined with HST observations have lead to unambiguous identifications with cataclysmic variables, RS CVn binaries, and millisecond radio pulsars.

1. Introduction

From the first maps of the X-ray sky it was already apparent that globular clusters are special also in X-rays. Of the ~ 200 permanent or transient bright X-ray sources in our galaxy, thirteen are now known to reside in a globular cluster. More sources were discovered with more sensitive instruments, and we have just crossed the brink to a spate of discoveries with Chandra/AXAF and with Newton/XMM. I start this review with a brief survey of the types of X-ray sources that may be detected in globular clusters, and their various formation mechanisms. I then discuss the bright ($L_x \gtrsim 10^{36}$ erg s $^{-1}$) cluster sources in our galaxy, in particular their preference for dense cores and the proof that they are accreting neutron stars, before assessing the change in perspective due to the first Chandra observations of globular clusters in our own and other galaxies. Finally, I describe the dim ($L_x \lesssim 10^{35}$ erg s $^{-1}$) sources from a ROSAT census, and compare the Chandra observations of ω Cen – described in more detail by Cool in these proceedings – with those of other clusters.

2. Typology and formation mechanisms

The various types of X-ray sources that one may expect to find in a globular cluster are depicted in Fig. 1. These types are selected on the basis of their

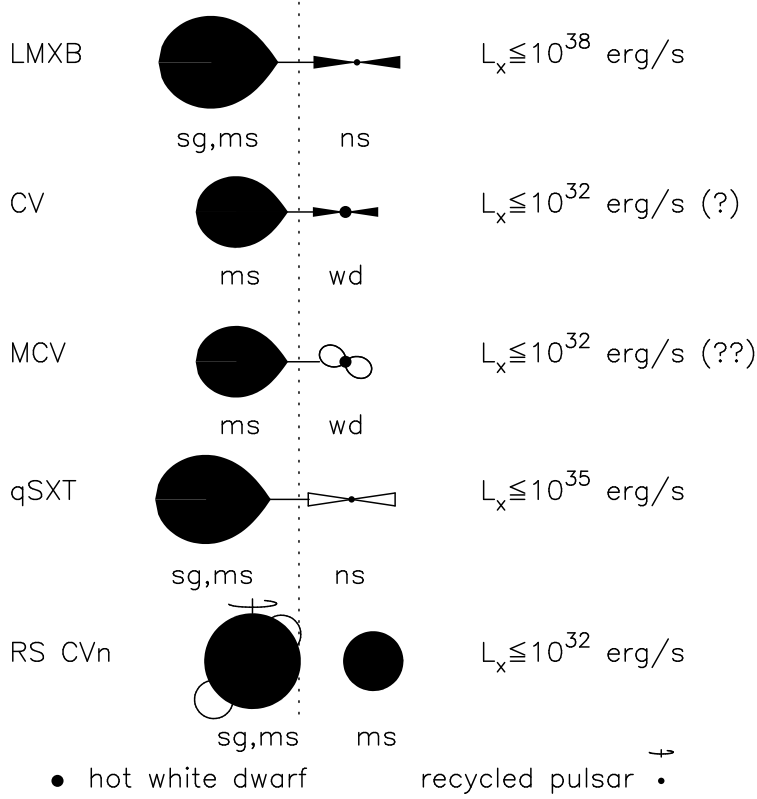


Figure 1. The various types of objects suggested as X-ray sources in globular clusters. Binaries from top to bottom: low-mass X-ray binaries, cataclysmic variables, magnetic cataclysmic variables, quiescent soft X-ray transients – in all of these the luminosity is due to mass transfer – and RS CVn binaries, in which magnetic activity produces the X-rays. Luminosities in the 0.5-2.5 keV range are indicated on the right. Single stars that emit X-rays include hot white dwarfs, and recycled pulsars. Recycled pulsars also occur in binaries, with an undermassive white dwarf companion. sg, ms, ns and wd stand for (sub)giant, main-sequence star, neutron star and white dwarf.

luminosity, as observed in the galactic disk where unambiguous identifications are possible also for less accurate X-ray positions, with the added criterion that they occur in an old population. This latter constraint excludes objects like supernova remnants or T Tau stars.

The brightest sources, with ($L_x \gtrsim 10^{36}$ erg s $^{-1}$), are neutron stars or black holes accreting from a main-sequence or (sub)giant companion star. Such *low-mass X-ray binaries* are the only option for the bright X-ray sources. For the dimmer sources, various types are possible. Some neutron stars and black holes accrete at high rates only during outbursts that typically last a month. Between such outbursts, such soft X-ray transients have much lower luminosities, down to 10^{32} erg s $^{-1}$ for accreting neutron stars, and to 10^{30} erg s $^{-1}$ for accreting black

holes (e.g. Rutledge et al. 2000). White dwarfs may also accrete matter from a companion; such binaries are called *cataclysmic variables*, or *magnetic cataclysmic variables* if the white dwarf has a strong magnetic field which disrupts (part of) the accretion disk. The X-ray luminosities of cataclysmic variables in the galactic disk (Verbunt et al. 1997) are difficult to determine, because of uncertain distances. In addition, most of the luminosity may be emitted at soft ($\lesssim 0.5$ keV) X-ray energies and in the extreme ultraviolet, strongly affected by interstellar absorption, which often is difficult to quantify. To minimize this problem, all X-ray luminosities in this paper are in the range 0.5–2.5 keV, unless specified otherwise. The orbital periods of all these binaries are on the order of hours for main-sequence donors; and of days for (sub)giant donor stars.

In close binaries, stars can obtain or retain rapid rotation velocities even at old age, and thus become or remain magnetically active. Such magnetically active binaries are called *RS CVn* systems, and are X-ray emitters (Dempsey et al. 1993). In the strict definition RS CVn systems contain a (sub)giant; I will use a wider definition, which includes main-sequence binaries, also called BY Dra systems.

Two types of single stars complete the list of possible sources of X-rays: hot white dwarfs, and recycled radio pulsars. The emission of hot white dwarfs is very soft, and will be detectable only in globular clusters with very small interstellar absorption (compare the work on M 67 by Belloni et al. 1998). Recycled pulsars are neutron stars that once accreted matter from a binary companion, and by this process were spun up to rapid rotation ($\lesssim 0.1$ s); for this reason they are often referred to as millisecond pulsars. When the accretion ended, the neutron star switched on as a radio pulsar. Apart from the rapid rotation, recycled pulsars have weak magnetic fields and are often accompanied by an undermassive ($\lesssim 0.4M_{\odot}$) white dwarf, and sometimes by an ordinary white dwarf, the remnant of the donor star. Their X-ray emission is analyzed by Becker & Trümper (1999).

In the galactic disk, all binary X-ray sources, including recycled pulsars, evolve from primordial binaries (e.g. Verbunt 1993). In globular clusters, two additional processes are possible: tidal capture and exchange encounter (reviewed by Hut et al. 1992). In a tidal capture, one star (in particular a neutron star or white dwarf) raises tides on a main-sequence or (sub)giant star in a close passage; the energy of the tides is taken from the relative motion, and the stars become bound, as the tidal energy is dissipated. In an exchange encounter, a star encounters a binary and forms a temporary triple with it; one star is then expelled (usually the star with the lowest mass) and the other two remain bound. In this way, a neutron star or white dwarf can be exchanged into a binary. The frequency of occurrence of both tidal capture and exchange encounters, the *collision number*, scales roughly with the square of the number density of stars and with the volume of the core, where most encounters occur.

For the formation of X-ray sources in globular clusters the relative importance of evolution of primordial binaries on one hand, and stellar encounters on the other hand, depends on the source type, and on the encounter frequency in the cluster. Many primordial binaries evolve into RS CVn systems; therefore all RS CVns in globular clusters are probably also formed from the evolution of a primordial binary. Extremely few primordial binaries evolve into low-mass

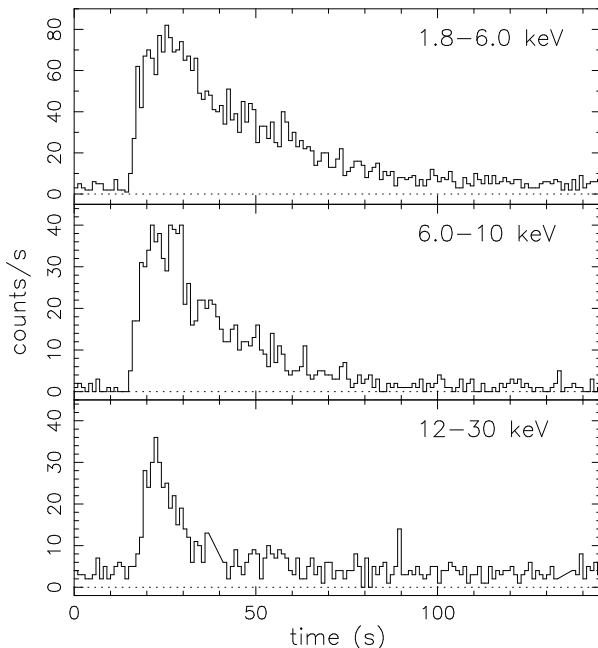


Figure 2. X-ray burst of NGC 6440 observed on 26 Aug 1998 with BeppoSAX. The faster decline at higher energies is evidence of a thermonuclear burst, and shows that the X-ray source is a neutron star. Adapted from *in 't Zand et al. (1999)*.

X-ray binaries (including soft X-ray transients) and on to binaries with recycled pulsars; therefore all X-ray sources in globular clusters with a neutron star are likely formed from stellar encounters. The situation with cataclysmic variables is intermediate between these extremes. In a low-density cluster with a high total number of stars, like ω Cen, most cataclysmic variables may have evolved from primordial binaries. In a cluster with a dense core where stellar encounters are frequent, like 47 Tuc, most cataclysmic variables may have formed in stellar encounters.

The situation in reality is more complicated and less well understood than the above description suggests, as discussed in more detail by Davies in this volume. The efficiency of tidal capture and the number and properties of binaries suitable for exchange encounters in globular clusters are uncertain. The number of neutron stars in globular clusters is uncertain by an order of magnitude. A binary formed by a stellar encounter in a very dense cluster can be destroyed again in a subsequent encounter. In addition, many aspects of binary evolution are not well understood: estimates for the life time of low-mass X-ray binaries or of cataclysmic variables differ by an order of magnitude. It must be concluded that the apparent accuracy of numbers produced in detailed simulations of the formation of X-ray binaries in globular clusters is spurious.

3. Luminous sources

A luminous X-ray binary may have a neutron star or a black hole as the accreting star. In the course of detailed studies of the cluster sources in our galaxy, it has been found that 11 of the 12 (now: 11 of 13; see below) luminous cluster sources show X-ray bursts (the most recent addition is NGC 6440, see Figure 2). Such

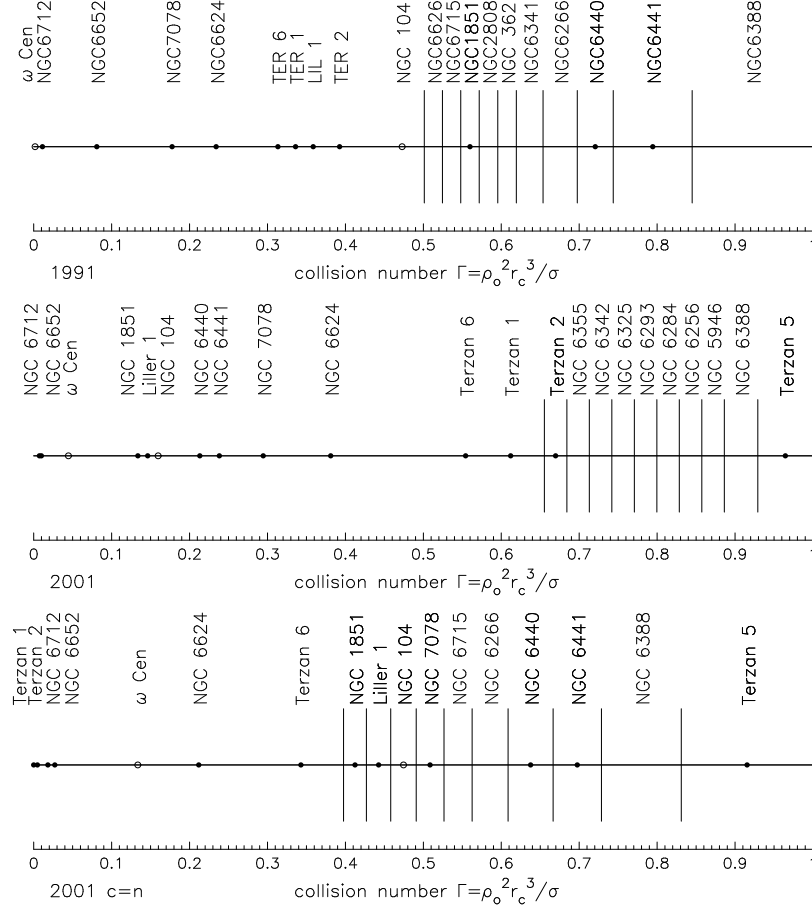


Figure 3. To test the collision hypothesis for bright X-ray sources, one orders the globular clusters on their collision number Γ , and assigns them a line section proportional to Γ . The clusters with an X-ray source should then be distributed homogeneously along the line. The top figure reproduces this test from Predehl et al. (1991), based on cluster parameters from Chernoff & Djorgovski (1989; their list does not include Terzan 5); a \bullet indicates a cluster with a bright X-ray source; for comparison ω Cen and 47 Tuc are indicated \circ . The ten clusters with largest Γ are delineated. The middle graph is an update for new cluster parameters (Harris 1996; version of June 22, 1999). In both, collapsed clusters are treated approximately by setting the central density ρ_o to $10^6 M_\odot \text{pc}^{-3}$ and the core radius r_c to 0.1 pc, i.e. all collapsed clusters have the same collision number. In the lower graph, the collision number for collapsed clusters is computed from their central density and core radius as for other clusters, to illustrate the effect of different treatments of collapsed clusters. All three versions pass the Kolmogorov-Smirnov test for a homogeneous distribution.

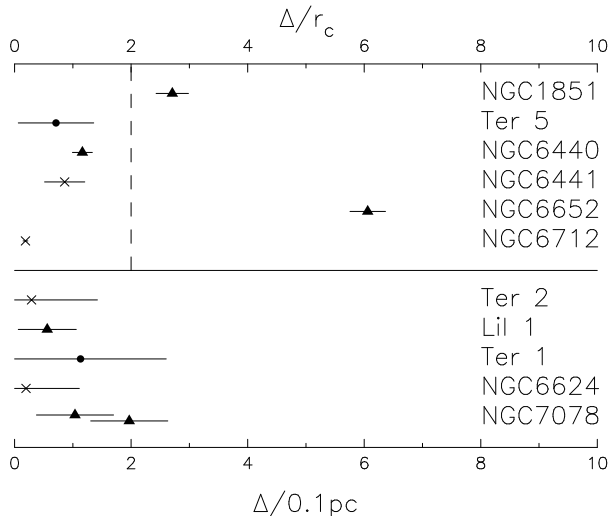


Figure 4. Distance to the cluster center of the bright X-ray sources, in units of the core radius; or of 0.1 pc for collapsed clusters. \times , \bullet , and \triangle indicate Einstein, Rosat, and Chandra positions (the latter taken from Homer et al. 2001a,b, Heinke et al. 2001, Pooley et al. 2001b, White & Angelini 2001). Uncertainties include an assumed $1''2$ uncertainty in the cluster center.

bursts are interpreted as sudden thermonuclear fusion into carbon of a layer of helium on the surface of a neutron star; thus every burster is a neutron star. The dearth of black hole accretors in globular clusters has been explained as follows. Once the more massive stars in a cluster have evolved, black holes are the most massive objects, sink towards the cluster center, and turn into black-hole binaries via exchange encounters. Encounters between black-hole binaries lead to large recoil velocities and virtually all black holes are thus shot out of the cluster (Portegies Zwart & McMillan 2000).

If the formation of low-mass X-ray binaries is due to close stellar encounters, one predicts that the probability of a cluster to contain such a binary is proportional to its collision number $\Gamma \equiv \rho_c^2 r_c^3 / \sigma$, where ρ_c and σ are the central density and velocity dispersion, and r_c is the core radius. One also predicts that most such sources reside in or near the cluster core. It appears that these predictions are correct (Verbunt & Hut 1987), as illustrated in Figures 3, 4. It should be noted that precise tests are difficult, given the uncertainty in how to treat collapsed clusters; and in the values of the cluster parameters. Three versions of the test are illustrated in Figure 3. The effect of the uncertainty in cluster parameters is illustrated by the difference between the top two graphs, which use the same equations, but different cluster catalogues. The effect of different treatments of collapsed clusters is illustrated by the difference between the lower two graphs. In the lower graph, collapsed clusters are treated like ordinary clusters; the presence of bright sources in Terzan 1 and 2 is then unexpected, as these clusters have a low collision number. In the top two graphs, the central density and core radius, and thus the collision number, of any collapsed cluster is set to a fixed number – a rather arbitrary procedure. Alternatively (and better justified) one can apply the test to ordinary, non-collapsed clusters only (see Predehl et al. 1991).

The dominant variation of the collision numbers is due to the variation in central density over more than 6 orders of magnitude between clusters; in contrast, the core radii (expressed in parsecs) and velocity dispersions vary much

less (by ~ 2 and $\lesssim 1$ order of magnitude respectively). It may be noted also that the velocity dispersion is not taken from observations, but computed assuming a King model as $\sigma \propto r_c \sqrt{\rho_o}$; effectively therefore $\Gamma \propto \rho_o^{1.5} r_c^2$.

Of the five orbital periods now known (most recent additions: NGC 6440, in 't Zand et al. 2000, and NGC 6712, Homer et al. 1996) two are ultra-short at 11.4 and 20.6 minutes, which indicates white dwarf donors. Two other systems may have such short periods as well (Homer et al. 2001a). This high fraction requires explanation. Comparison of NTT observations made before and during the 1998 outburst of the transient bright X-ray source in NGC 6440 provided an optical counterpart, the first one found for a transient in a cluster (Verbunt et al. 2000).

Chandra has already produced two interesting results for the bright cluster sources in our galaxy. First, White & Angelini (2001) have found that M 15 contains two bright sources, so close that earlier satellites couldn't separate them. This resolves the puzzling combination of properties found for the M 15 source: on the one hand, the extended partial eclipse of the X-ray source indicated that the central source is not directly observed and that the X-rays observed on earth are scattered from a corona above the accretion disk; on the other hand a thermonuclear burst of the source reached the Eddington limit, proving that the neutron star is observed directly. Apparently, one source is the disk corona source, and the other source is the burster. The occurrence of two sources was expected in clusters with very high collision numbers rather than in M 15 (NGC 7078) with its not very high collision number (see Fig. 3). The occurrence of two sources in M 15 thus suggests a higher number of potential bright X-ray sources in globular clusters than hitherto suspected. The absence of a bright source in ω Cen is not surprising, given its low collision number.

The second interesting Chandra result is its proof, thanks to a more accurate position, that the bright source in NGC 6652 is at 6 core radii from the cluster center (Heinke et al. 2001), which indicates that this source is the result of an exchange encounter rather than of a tidal capture.

The improved sensitivity and high spatial resolution of Chandra has led to the detection of many X-ray sources in the globular clusters of other galaxies, including NGC 4697 (Sarazin et al. 2000) and NGC 1399 (Angelini et al. 2001). Remarkably, some clusters are very bright, $\gtrsim 10^{39}$ erg/s. This, and the softness of their X-ray spectra, suggests that these cluster sources are black holes. Clusters with luminosities $\gtrsim 10^{38}$ erg/s may be examples of clusters with several bright low-mass X-ray binaries. The occurrence of such bright sources in clusters of these galaxies is probably a consequence of the very large numbers of clusters that these galaxies have, i.e. of the presence of clusters with more extreme properties than the clusters in our galaxy (in terms of mass, central density and core size). The luminosity distribution of bright globular cluster sources in our galaxy is dominated by small-number statistics, which hampers statistical comparison with the bright sources in clusters of other galaxies.

4. Dim sources

Dim sources in globular clusters were first detected with Einstein by Hertz & Grindlay (1983), who suggested that most of them are cataclysmic variables.

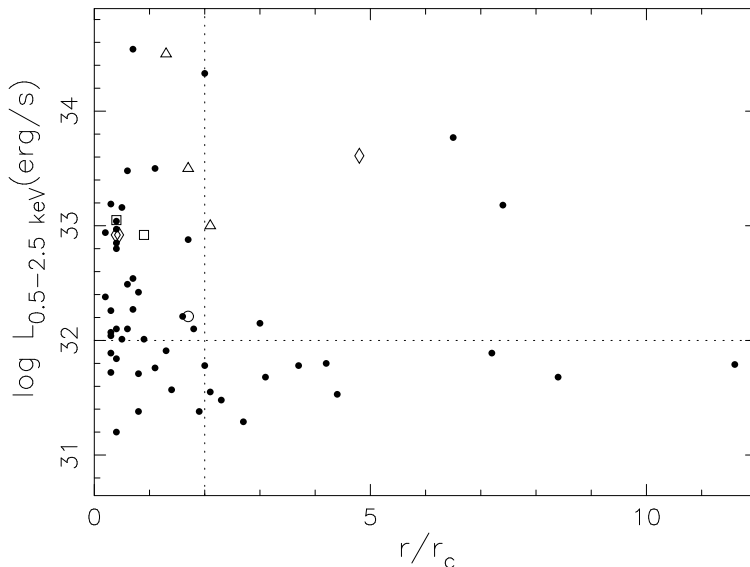


Figure 5. X-ray luminosity of dim sources in globular clusters as a function of distance to the cluster center, in units of the core radius. \bullet ROSAT source, \square, \circ , sQXT in 47 Tuc, ω Cen; \triangle, \diamond Chandra sources in Liller 1 and NGC 6652. The horizontal dotted line indicates the approximate limit to the X-ray luminosity of cataclysmic variables in the galactic disk. A source at $r = 26r_c$ is omitted.

From the observation that cataclysmic variables in the galactic disk usually have X-ray luminosities $\lesssim 10^{33}$ erg/s, Verbunt et al. (1984) suggested that the more luminous dim sources in globular clusters are neutron stars accreting at a low rate, i.e. quiescent transients.

A complete census of all 57 dim sources detected with ROSAT is provided by Verbunt (2001). Figure 5 shows the X-ray luminosity of the sources from that census, as a function of distance to the cluster center. Most sources are within 2 core radii from the center. A significant population of dim sources is also present further out, especially at luminosities $\lesssim 10^{32}$ erg/s; some of these sources may be primordial cataclysmic variables and RS CVn systems. At luminosities $\gtrsim 10^{33}$ erg/s, where most sources are probably quiescent transients, two ROSAT sources are detected well outside the core: these may have formed via exchange encounters. The ROSAT data indicated that the X-ray spectra of globular clusters are soft, compatible with those of quiescent transients.

One remarkable result from the ROSAT census is that the X-ray emission of most globular clusters per unit mass is lower than that of the old open cluster M 67 (Verbunt 2001). Our understanding of this result is not helped by the fact that the three most luminous X-ray sources in M 67 are mysterious: one is a triple containing two blue stragglers; two are located below the subgiant branch in the Hertzsprung Russell diagram and we do not understand their evolutionary status (Belloni et al. 1998, van den Berg et al. 2001).

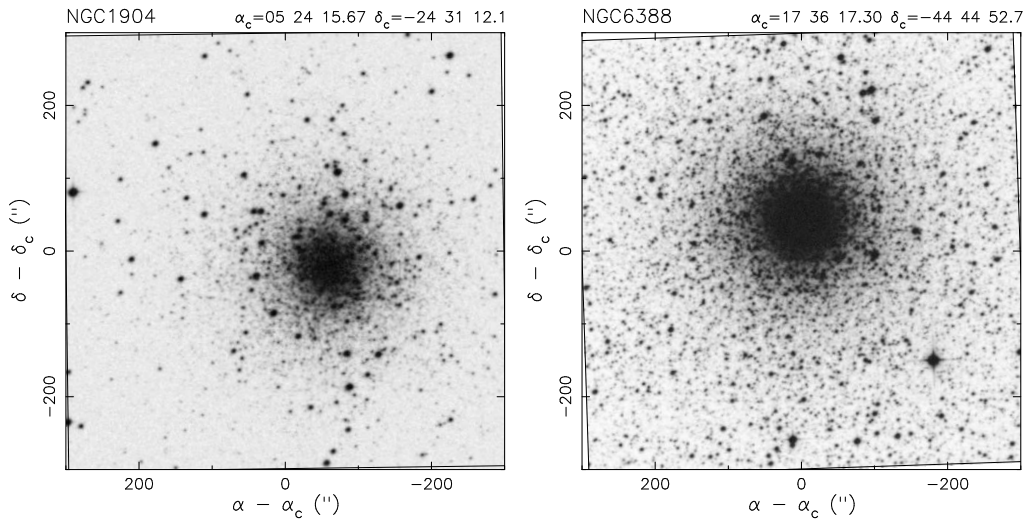


Figure 6. Positions of two dim sources, with $L_x \gtrsim 10^{33}$ erg/s, discovered with ROSAT in the globular clusters NGC 1904 and NGC 6388. The images from the Digitized Sky Survey are centered on the X-ray positions, to illustrate the offset to the cluster center.

The spatial resolution of Chandra made possible the first detection of dim sources in clusters with bright sources, viz. in Liller 1 and in NGC 6652 (Homer et al. 2001b, Heinke et al. 2001). The luminosities of several of these suggests that they are quiescent transients, one well outside the core (see Figure 5).

The superior spatial resolution of Chandra further resulted in the discovery of dozens of sources in each of five clusters devoid of bright sources.

In ω Cen, a low-density cluster with a large core, ROSAT was already able to separate the X-ray sources, as shown in Figure 7; Chandra has added new sources to bring the total to 40 (Rutledge et al. 2001) or more (Cool, these proceedings). The brightest X-ray source in ω Cen (X7 from Verbunt & Johnston 2000, see Fig. 7) has a relatively soft spectrum, and probably is a quiescent soft X-ray transient. The presence of such a source in ω Cen is surprising: as argued in Sect. 2 above, binaries with neutron stars in globular clusters are most likely formed in close stellar encounters, but the number of such encounters in ω Cen is relatively low ($\sim 0.2\%$ of the encounter rate in all clusters together). Unless the soft X-ray transient in ω Cen is a statistical fluke, its existence indicates a large number of quiescent transients in the globular cluster system. Alternatively, the system could have evolved from a primordial binary (ω Cen has a mass of $\sim 3 \cdot 10^6 M_\odot$, see Meylan, these proceedings). This would indicate a rather larger fraction of primordial binaries evolving into binaries with a neutron star than hitherto thought possible; and thus also implies a large number of quiescent X-ray transients in the galactic disk.

In higher-density clusters, ROSAT failed to resolve all X-ray sources, even with sophisticated software, as illustrated in Figure 7: ROSAT did detect the brighter sources – and with these, the bulk of the X-ray flux – but in their glare could not detect the fainter sources. The first Chandra results have found many,

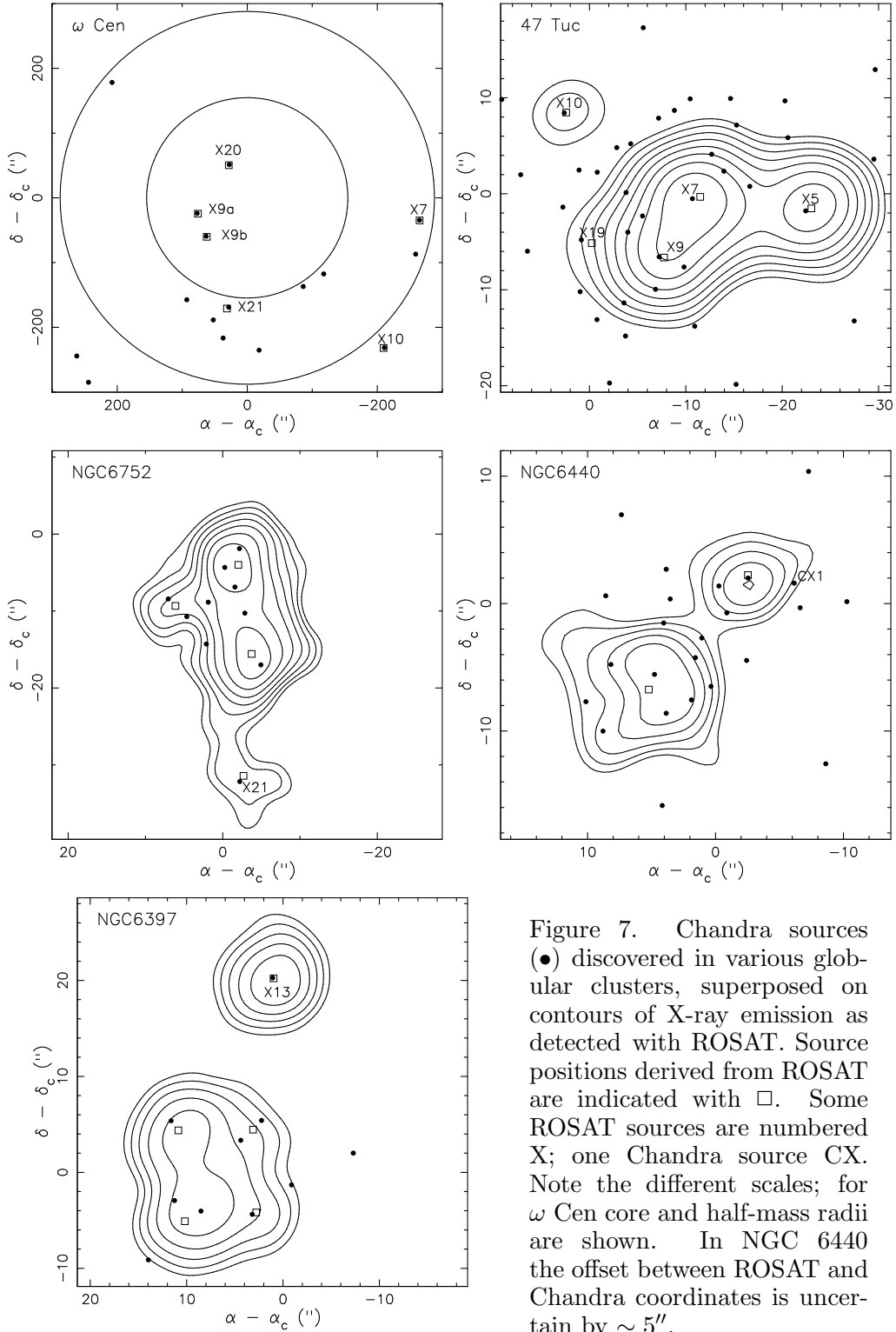


Figure 7. Chandra sources (\bullet) discovered in various globular clusters, superposed on contours of X-ray emission as detected with ROSAT. Source positions derived from ROSAT are indicated with \square . Some ROSAT sources are numbered X; one Chandra source CX. Note the different scales; for ω Cen core and half-mass radii are shown. In NGC 6440 the offset between ROSAT and Chandra coordinates is uncertain by $\sim 5''$.

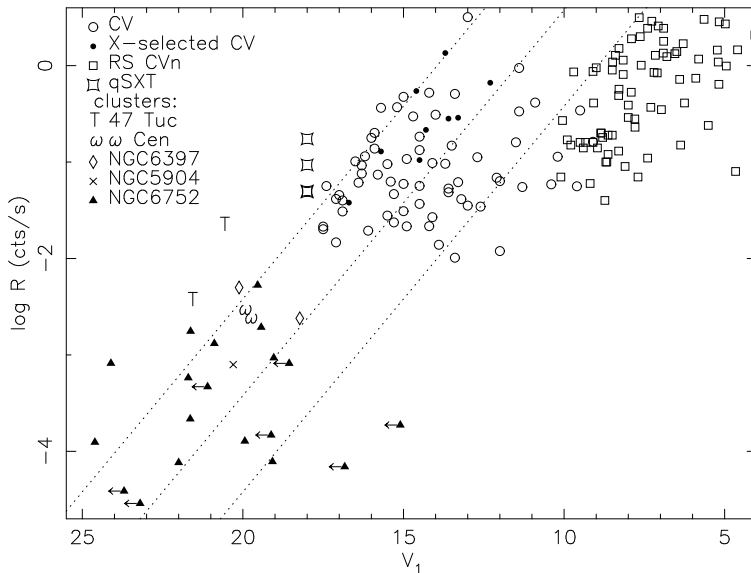


Figure 8. X-ray flux, expressed in ROSAT PSPC countrate R , as a function of visual magnitude, for cataclysmic variables, RS CVns and quiescent soft X-ray transients in the galactic disk, and for various optically identified dim X-ray sources in globular clusters. For NGC 6752 R is computed from Chandra countrates; and arrows indicate upper limits to the visual flux (from Pooley et al. 2001a). The dotted lines indicate constant ratios of X-ray to optical flux.

many dim sources: more than 100 in 47 Tuc alone (Grindlay et al. 2001a); 19 in NGC 6752 (Pooley et al. 2001a), 25 in NGC 6397 (Cool, these proceedings, Grindlay et al. 2001b¹), and 24 in NGC 6440 (Pooley et al. 2001b). Most of these sources are cluster members, rather than fore- or background objects. Of them, 2 in 47 Tuc (X5, X7 in Fig. 7), 1 in NGC 6397 (X13 in Fig. 7) and some 5 in NGC 6440 are quiescent soft X-ray transients. (Perhaps it is safer to say that they are neutron stars accreting at low luminosity, since we do not know when or whether they ever show outbursts.²)

Most ROSAT positions have accuracies of $\sim 5''$, which in a dense cluster core is insufficient for unambiguous optical identifications, as shown by wrong identifications in e.g. 47 Tuc and M 13 (discussed on the basis of more accurate ROSAT positions in Verbunt & Hasinger 1998, Verbunt 2001). However, objects with $H\alpha$ emission and variability on time scales of hours – presumed to be cataclysmic variables – have been suggested as counterparts for other ROSAT sources in 47 Tuc and NGC 6397, and were confirmed with Chandra (Grindlay et al. 2001a,b). Two variables in NGC 6752 have been identified with X-ray

¹The latter reference was published after the meeting; I include its results, also in Fig. 7, for completeness

²In fact, during the conference one of the sources in NGC 6440, CX1 in Fig. 7, did go into outburst! see in 't Zand et al. (2001)

sources, after correction of their optical positions (Pooley et al. 2001a). The optical to X-ray flux ratio of dim sources can be compared with that of the various proposed types of counterparts; this is done in Figure 8. The X-ray to optical flux ratio of optically identified sources in ω Cen (Carson et al. 2000), NGC 5904 (Hakala et al. 1997) and NGC 6397 (Cool et al. 1995, Verbunt & Johnston 2000) are in the range found for cataclysmic variables in the disk. These sources thus probably are cataclysmic variables. The source in NGC 5904 is interesting in being located in the outskirts of the cluster, at 11.6 core radii; it is a dwarf nova. Two sources in 47 Tuc (X9 and X19 of Verbunt & Hasinger 1998, see Fig. 7) and one in NGC 6752 (CX6 of Pooley et al. 2001a, X21 in Fig. 7) have an X-ray to optical flux ratio higher than those for cataclysmic variables in the disk, and more similar to those of the quiescent soft X-ray transients Cen X-4 and Aql X-1. However, the Chandra spectra of these sources are harder than the quiescent X-ray spectra of transients. Thus these sources are probably cataclysmic variables. The presence of $H\alpha$ emission lines is also used as an indicator that a source is a cataclysmic variable. Whereas this conclusion is often correct, it is worth noting that quiescent X-ray transients also may show substantial $H\alpha$ emission lines (for example Cen X-4, van Paradijs et al. 1987). $H\alpha$ emission by itself is not definite proof for a cataclysmic variable.

5. Conclusions

The distribution of bright X-ray sources over clusters with different encounter rates, as expressed in the collision number, is compatible with the hypothesis that these sources are formed in close encounters of neutron stars with other cluster stars or with binaries. The spatial distribution of low-luminosity sources in globular clusters shows a concentration towards the core, again compatible with the hypothesis that many sources are formed in close encounters. Sources far away from the cluster centers may have evolved from primordial binaries, or – if they contain a neutron star – from a close encounter of a neutron star with a binary, the recoil of which brought them to their current location. For future studies, a calculation of encounter rates in collapsed clusters would be very useful; and more generally calculations of encounter rates in evolving clusters. After all, the current encounter rate in a cluster need not be representative for sources formed long ago.

ω Cen was not expected to contain binaries with a neutron star: its encounter rate is relatively low, and in agreement with this, no bright X-ray source or recycled radio pulsars have been found in ω Cen. The discovery of a binary in which – based on its luminosity and soft X-ray spectrum – a neutron star accretes at a low-rate from a companion suggests that there may be rather more binaries with neutron stars in the galactic globular cluster system than previously expected. The major uncertainties in theoretically predicting the formation rates of such binaries are the uncertainty in the number of neutron stars formed with velocities sufficiently small that they are retained in the globular cluster; and the cross sections of the various mechanisms which may put a neutron star in a binary.

A new era has started with Chandra. The study of large numbers of globular clusters in other galaxies will hopefully elucidate the relation between cluster

properties – total mass, central density, and core radius – and X-ray properties. In particular, the discovery of accreting black holes in these clusters is interesting. The accurate positions of sources in clusters in our own galaxy enables unambiguous identifications with radio and optical sources. A first result from this is that several of the cataclysmic variables in globular clusters have a higher X-ray to optical flux ratio than cataclysmic variables in the galactic disk.

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